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ADVANCED CERAMICS for NAVY AIR VEHICLE APPLICATIONS

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NAWC-AD
Patuxent River, Maryland

With helpful input from D.Carper, J. Steibel, V. Barry (GE), D. Foley (Honeywell Adv Ceram), K.Hatton (HCI), J. Armstrong & F. Zupank (HES), T. Carstensen (Sikorsky), R. Williams & K. Goodman (Bell), M. Rigaldi and T. Mulligan (ACR), M. Richman, A. Young, J. Bentz, L. Parish, J. Rubinsky, W. Voorhees, J. Young, A. Penterman, R. Kowalik (NAVAIR), D. Lewis (NRL).

Advanced/Toughened Ceramics and CMC's are Increasingly being Sought to Replace or Protect Metallic Components for Navy Air Vehicle Applications

- Ultra High Temperature Applications to meet performance goals e.g. 2400 F IHPTET combuster liners & turbine components (vanes, shrouds, airfoils).

- Intermediate Temp Applications, e.g. 1200F, IRS components
- Lighter Weight, ρ = 2.2, 4.4, 7.8, 8.2 g/cm3 for CMC, Ti, SS, Ni

- Higher Modulus

- TPS for short duration temp spikes

- Erosion & Wear Resistance

- LO Characteristics (RF and IR signatures)

Why Ceramics/CMCs

Evolution of Jet Engine Technology

	1942	Today	2005+
Thrust/Wt.	1.6:1	9:1	15:1
Turbine Inlet Temp.(F)	1500	2800	3000+
Engine Life(Hot Sections)	7.5	2000	4000
Fuel Efficiency	base	+46%	+65%

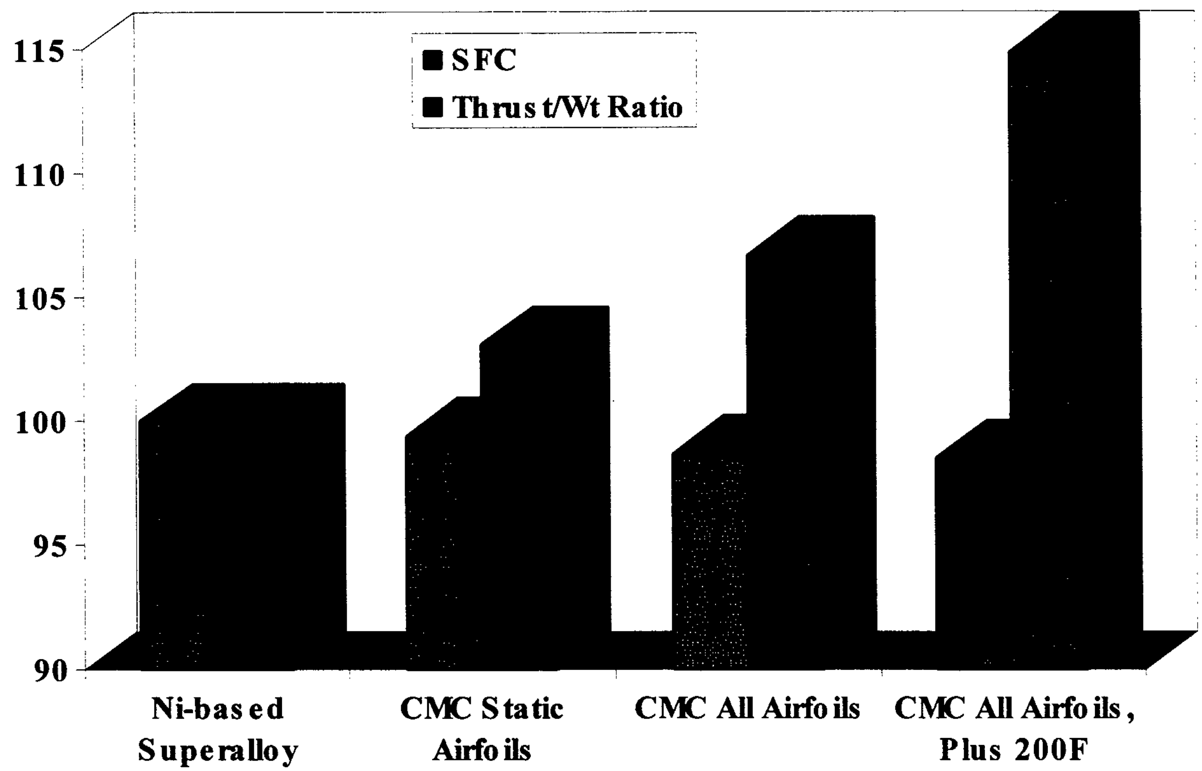
Why SiC/SiC* CMC

- High temperature, low weight material for combustor, turbine, turbine frame applications
- Low coefficient of thermal expansion for seal clearance control
- Potential for longer life, reduced emissions, growth margin, reduced weight, and increased performance

SiC/SiC CMC has significant advantages over Ni-based superalloys

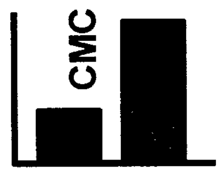
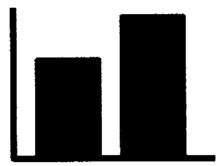
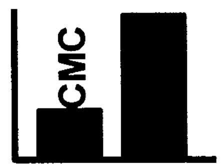
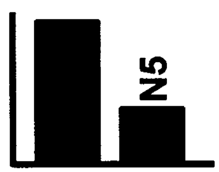
* SiC≡Silicon Carbide

Why SiC/SiC CMC



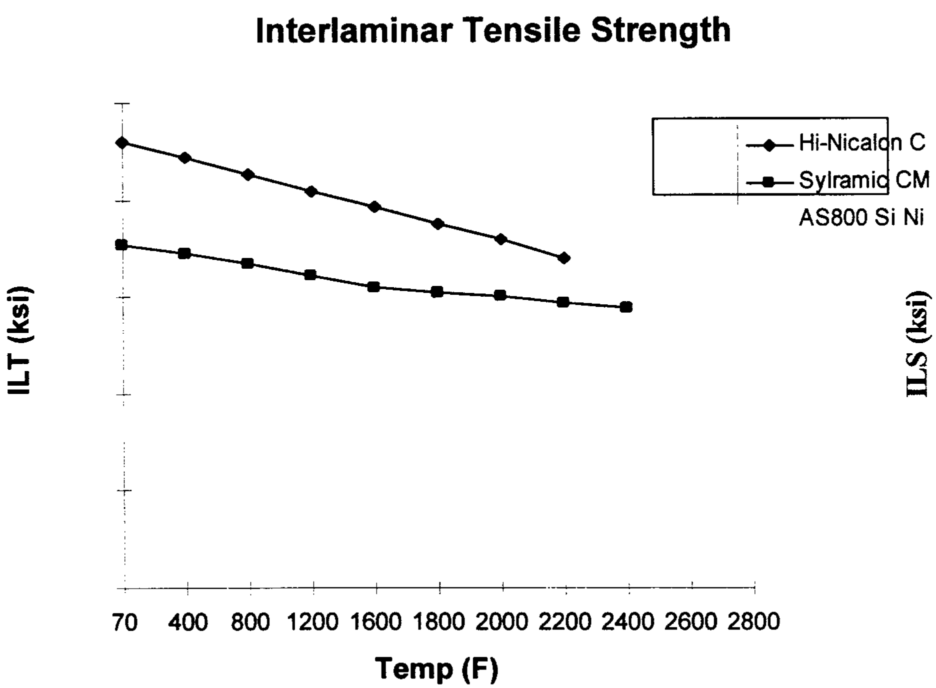
CMC has SFC and thrust/weight benefits over Ni-based superalloys

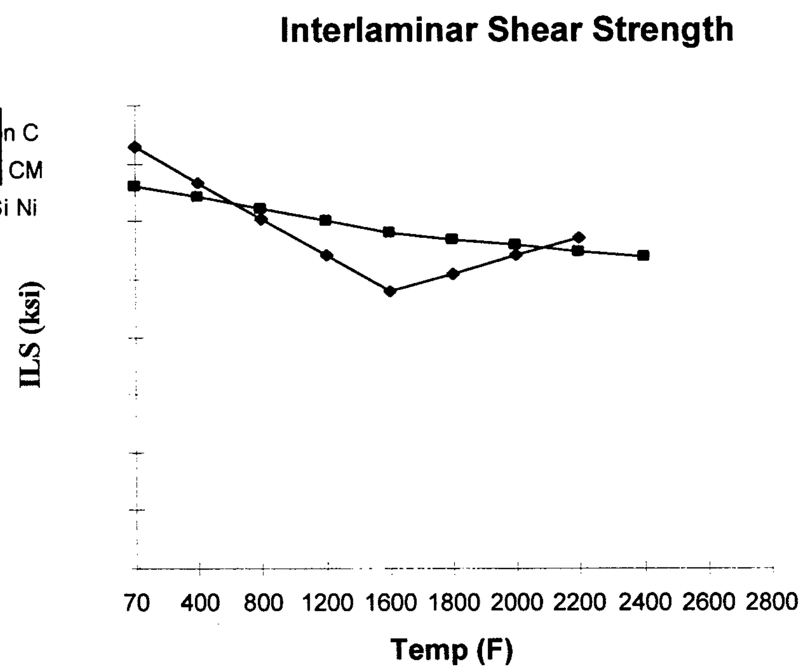
CMC* vs N5 Material Property Comparison

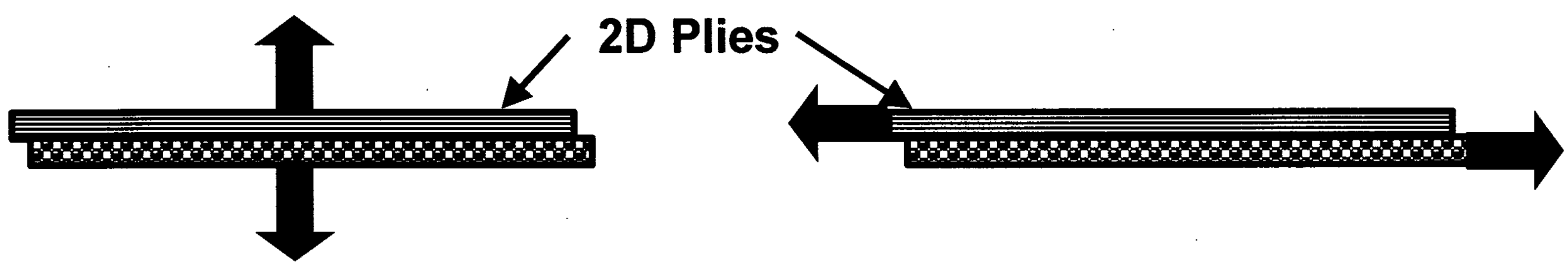
Material Property	Ratio	Impact on CMC Design
Density [ρ]		Lowers weight Increases response time
Thermal conductivity [K]		Drives thermal gradients Increases thermal stress
Coefficient of thermal expansion [α]		Lowers thermal stress & distortion
Young's modulus [E]		Increases thermal stress
Specific heat [Cp]		Higher at lower temperatures Decreases response time

*Melt Infiltrated, Hi-Nicalon

Low Interlaminar Strength

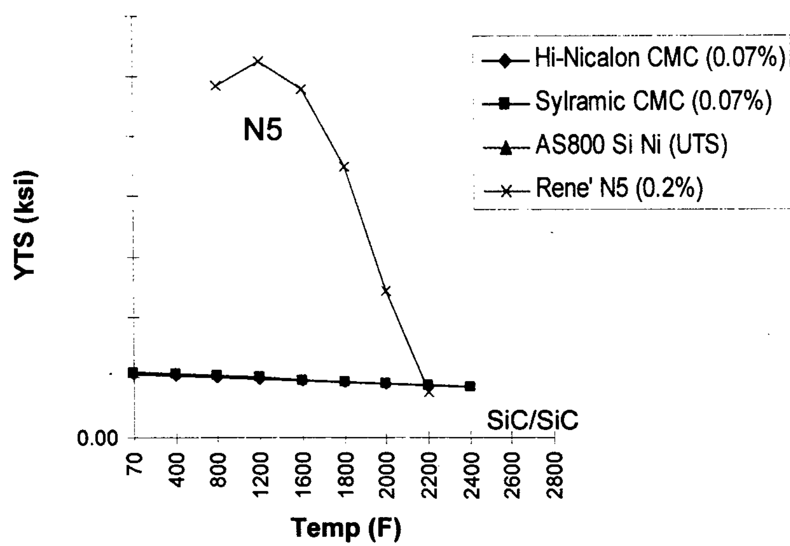




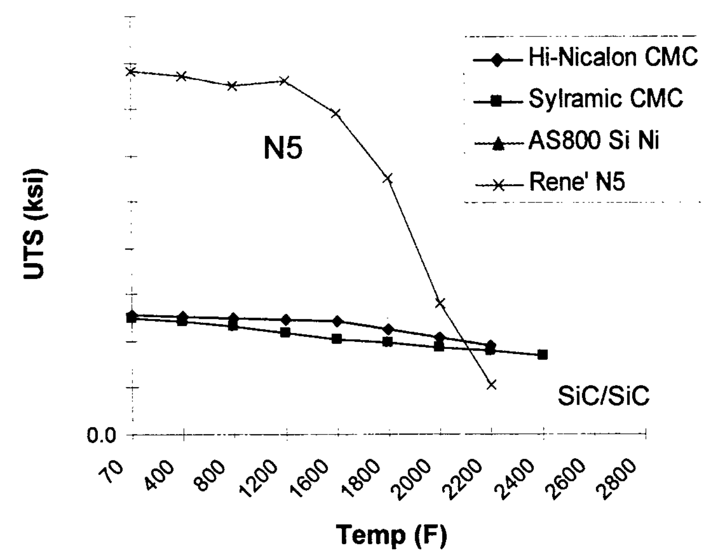


Low Tensile Strength Challenge to Design

Yield Tensile Strength



Ultimate Tensile Strength

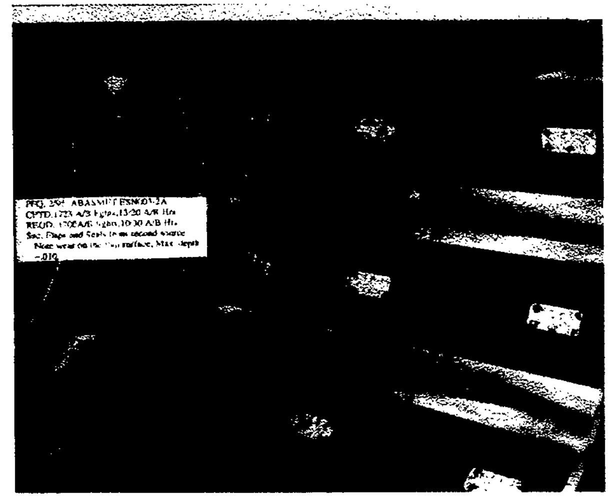


CMC Programs

- F414 Flaps & Seals
  - Flight Program
  - MANTECH Program
  - Affordability Program
- GE23A Component Technology Development
- X-31 Vector Program
- IHTPET
  - Combustor, JTAGG III, I
  - Vanes
- H60, H1 IR Suppressor, MANTECH
- AV-8/Pegasus
  - Turbine Vane Inserts
  - Blast Shield - Flight, Repair
- F-14/F110 Flameholder Inserts
- V-22 SDC Impeller

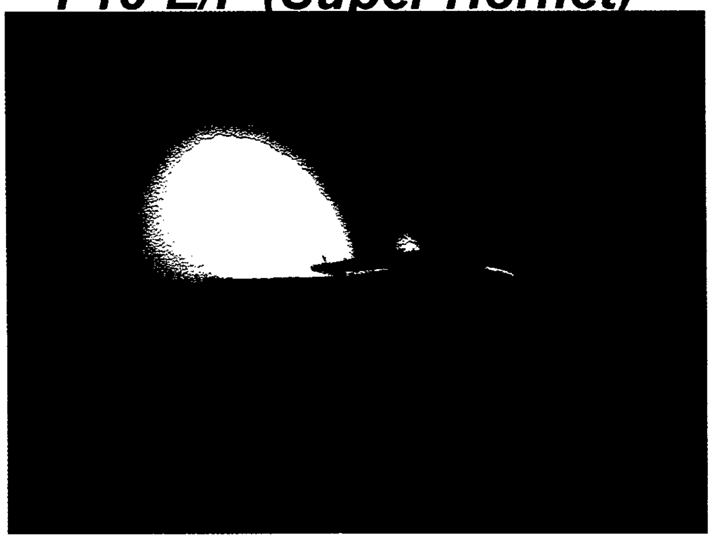
F414 CMC FLAPS & SEALS

Insertion Success: CMCs have enabled significant performance gains to be achieved with the F18.



- CMC System: BFG SiC/C with dual top coats
- top coats are CVI SiC and a glass frit outer coating for wear resistance and oxidation-protection.

F18-E/F (Super Hornet)



Breaking The Barrier

Status:

- Many components have logged over 800 hours flight time with significant A/B lights.
- Affordability/Life Cycle being addressed.
- Potential Programs to Address:
- reduction in thermal gradients ⇒ cracking (flaps)
- reduction in coating spallation ⇒ composite oxidation ⇒ component recession
- attachment design to prevent cracking from bending, ΔP VEN
- improved rub wear resistance

AFFORDABLE SIC/C CERAMIC EXHAUST COMPONENTS

Objective: Reduce the cost of SiC/C flaps and seals for the F414.
- Goal is a 20% cost reduction.

• Reduced Part Dimensional Inspection (4-5% savings).

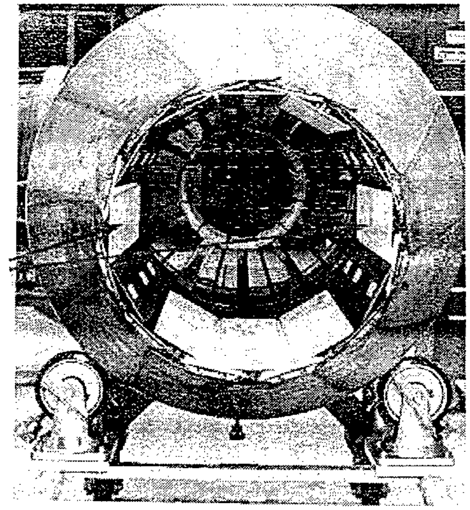
• Reduced CVD cycle time (2-3% savings).
- eliminate second CVD cycle.
- combine carbonization and pyrolysis - new BFG furnace.

• Lower Cost SiC fiber.
- substitute Tyranno ($400/lb) for Nicalon (15% savings).

BFGoodrich

F414 DIVERGENT FLAP & SEAL AFFORDABILITY PROGRAM

Objective: Qualify an alternate CMC system for the F414 flap & seal application that offers significant cost savings without a weight or life penalty.



Background:
GE IR&D program has developed an O-O CMC system (N720/AS) that is a viable replacement to SiC/C.

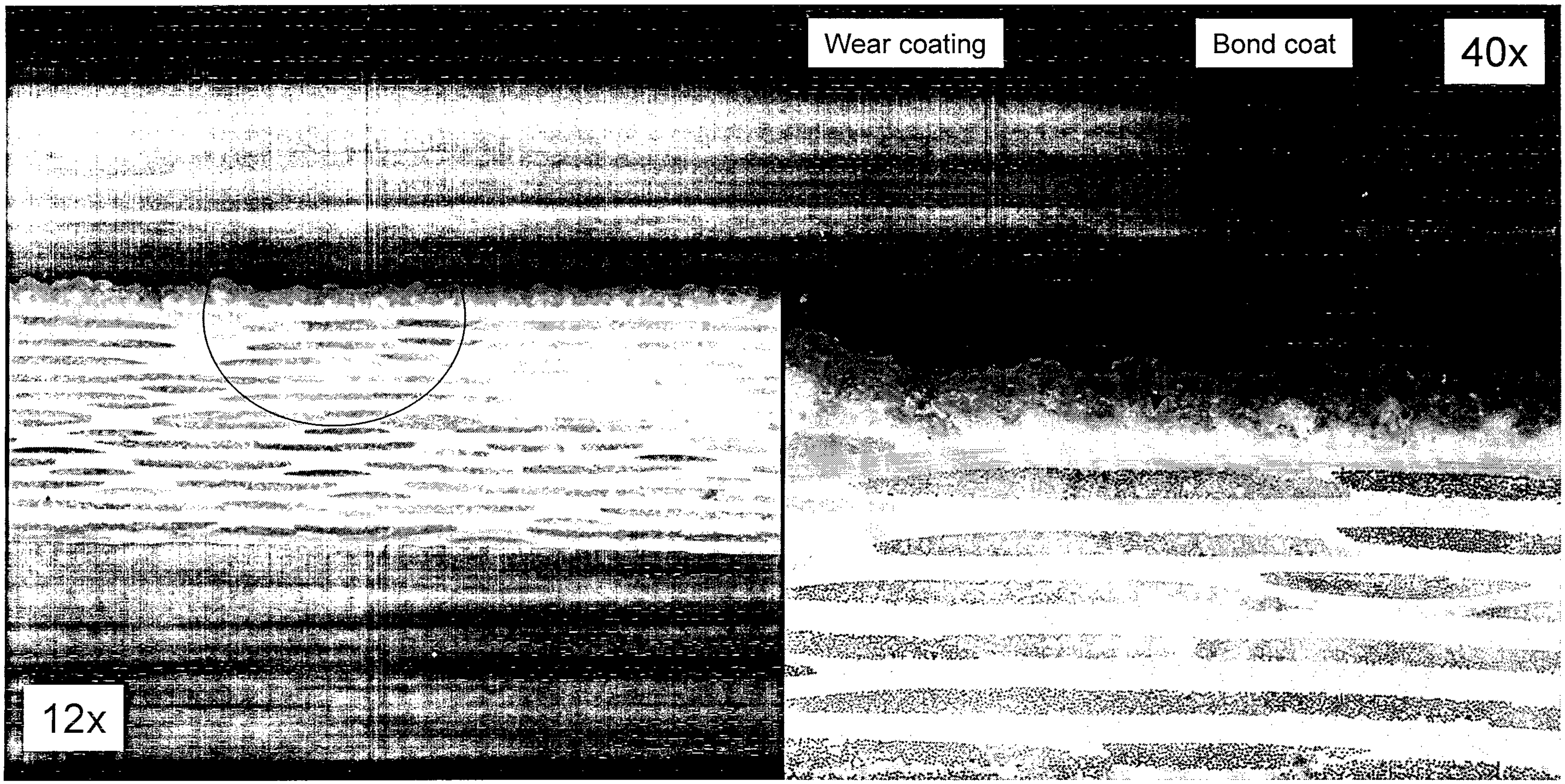
Benefits (O-O vrs existing SiC/C)
- Reduced material cost (approx. 25%)
- Oxidation not an issue
- Standardized manufacturing technology


Coating spall on flap without improved surface preparation and bondcoat addition

Status:

- Instrumented engine test - 85 hrs
- Wear resistant composite coating (AS)
- Production sources being identified for F&S mfg.
- Legal agreement established with Hexcel, Inc. first production lot in June, 00.
- NAVAIR- Environmental testing and qualification
- Engine Test on Vendor hardware, Apr, 01.

Wear Coating Application to Oxide CMC Flap

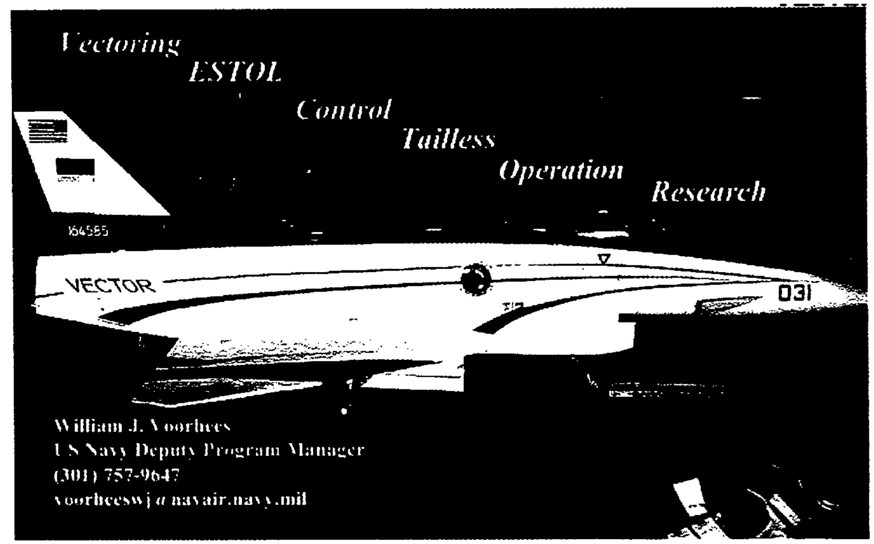


VECTOR PROGRAM

International (GER/US) Cooperative Program
- Follow-on to GER/US X-31 Enhanced Fighter Maneuverability (EFM) Program (1990).
- Use the single existing X-31 Aircraft

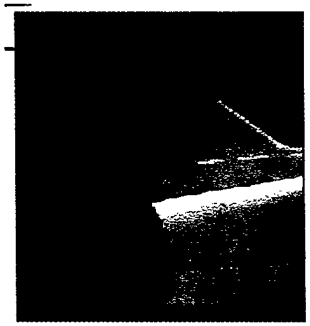
VECTOR Products
- Technology Development and Demonstration of
- **ESTOL** - Extremely Short Take-Off and Landing
- **AADS** - Advanced (Flush) Air Data System

All flight tests conducted at NAVAIR Patuxent River, MD



X-31 Experimental Aircraft
(Arrived at PAX on Apr. 13, 00)

THRUST VECTORING:
- controlling the direction of the engine exhaust to achieve dramatic aircraft maneuvers
- Carbon/Carbon composite paddles



The VECTOR Team

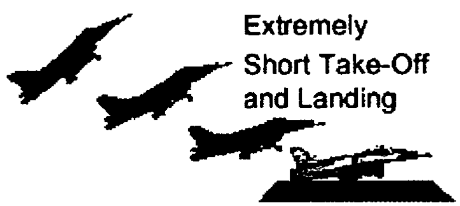
← MOA →

Naval Air Systems Command ↕ BOEING

Bundesamt für Wehrtechnik und Beschaffung (BWB) ↕ DaimlerChrysler Aerospace Military Aircraft

ESTOL

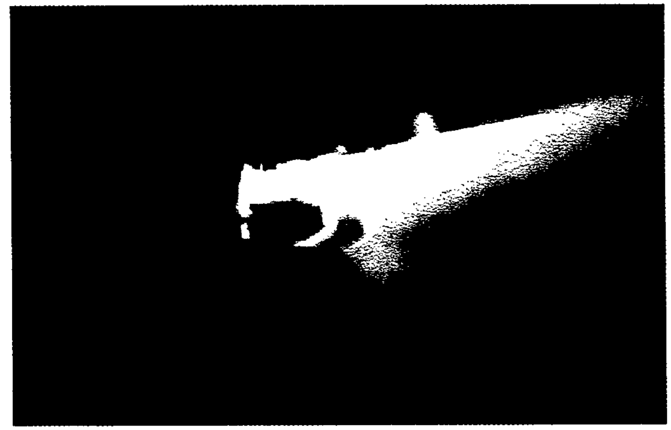
Extremely Short Take-Off and Landing



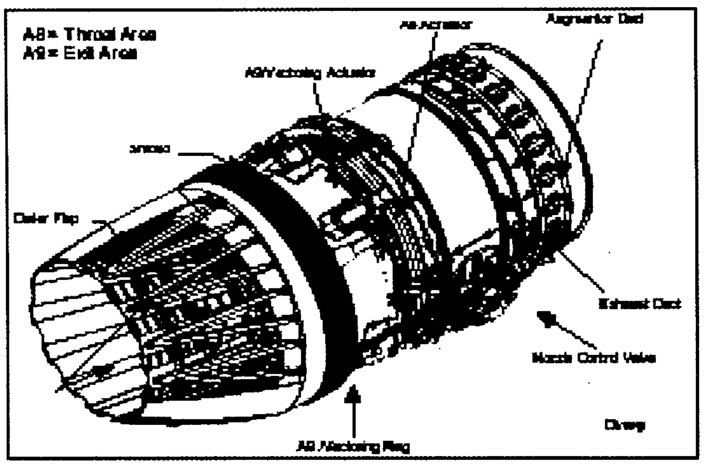
Multi-Axis Thrust Vectoring - Key Technology for the Demonstration

VECTOR

- **Multi-axis thrust vectoring**
  - Use of existing TV vane systems allows development of other technologies to proceed
  - Production nozzle not required for demos
    - » T/V paddle performance is sufficient
    - » Fail-safe redundancy sufficient



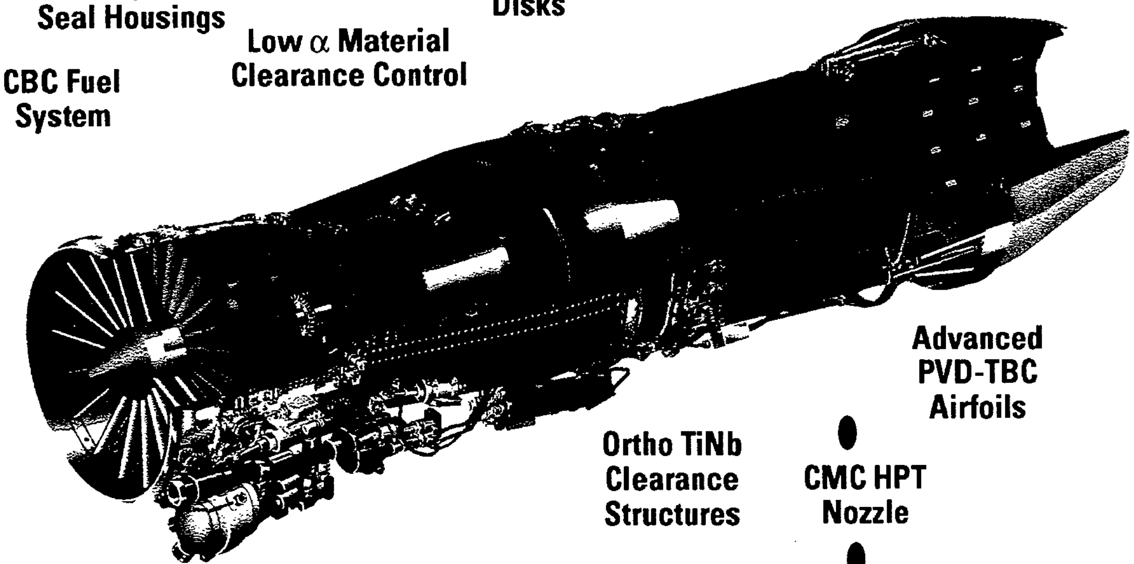
Thrust Vectoring Vanes Design



G.E. AVEN® Nozzle

- **AVEN®**
  - Performance representative of production systems
    - » Higher control power and rates
    - » Redundancy for full envelope fail safe
  - Broader range of control authority

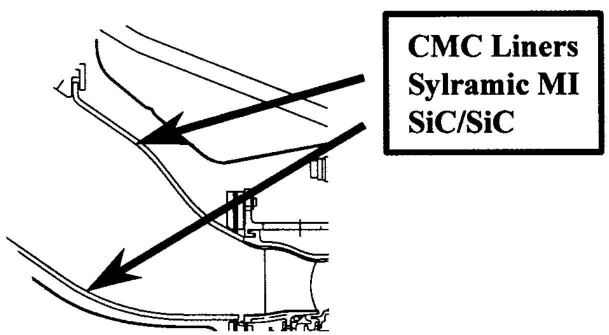
GE23A - ADVANCED TECHNOLOGY ENGINE
ADVANCED MATERIALS AND TECHNOLOGY



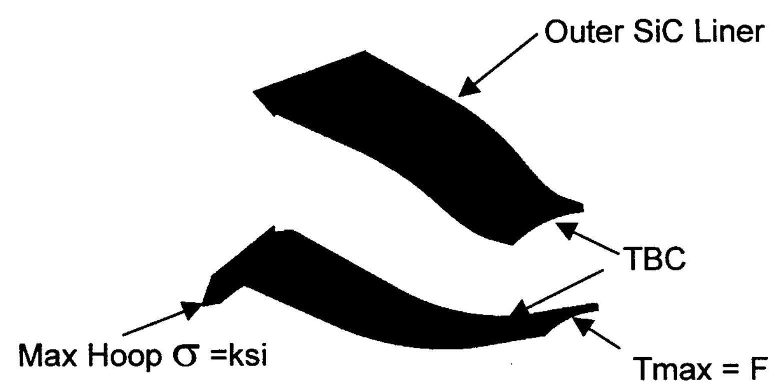
High Temperature Rise CMC Combustor (IHPTET/JTAGG III - Helicopter Engine)

OBJECTIVES
- Develop a full life combustion design w/Phase III T4 capability (+1000F).
- Reduce Pattern Factor (PF) to 0.13 from .25.
  - want more uniform combustor exit temp (longer turbine life downstream, e.g. vanes) which is achieved with highercombustor temp's and control of air flow, e.g. swirlers.
- Decrease Weight by 67%

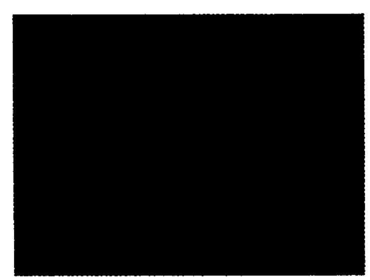
TECHNICAL CHALLENGES
- Achieve full life (2000hrs) under high heat load conditions while minimizing cooling requirements
- Maintain acceptable combustor performance & operability (aerodynamics and proper lighting) with an increased ΔT
- Limited structural capability of cmc liner material, i.e. designing with reduced stress tolerance.



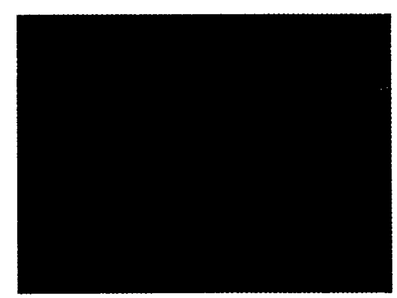
ANSYS/CFD Results



STATUS
- Full annular metal prototype, i.e. design, is being Rig tested.
- Full annular CMC scheduled for Rig Test in Sept, 00.



CMC Outer liner



CMC Inner liner

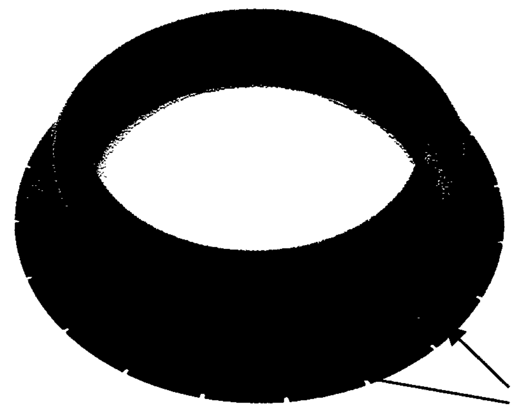
Cooling holes to be drilled following metal design test

High Temperature Rise Combustor
(IHPTET/JTAGG I - Helicopter Engine)

Objectives
- Used CMC liners as structural members, not insulative tiles
  - DuPont CG Nicalon/Enhanced SiC, triaxial braided architecture
- Design low-stress combustor with full life
- Measure CMC conditions during testing
- Demonstrate combustor in gas generator

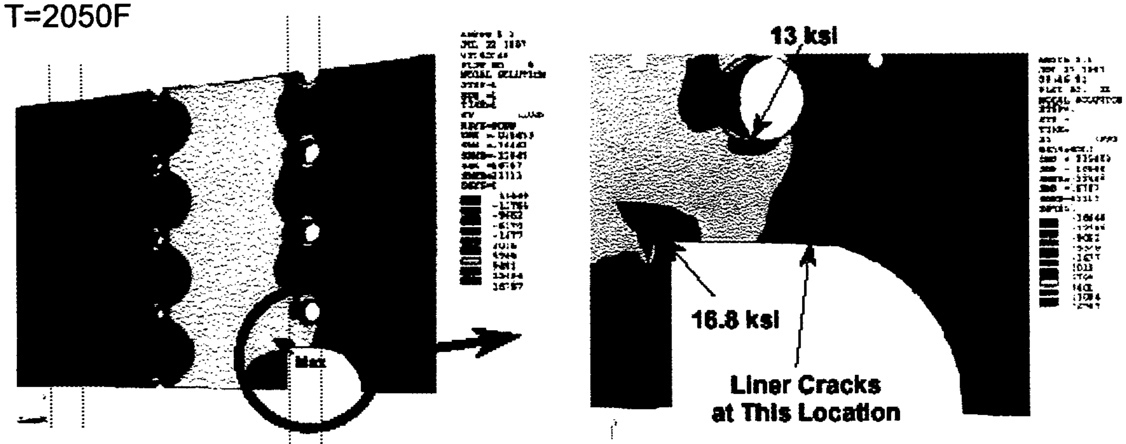
Results
- Rig Test - Combustor survived complete test - 30hr, 50 cycles
- Engine test - 11 hours 35 min's, (1hr 7 min at max power).
  - multiple cracks occurred on OD liner (initiated near "D" hole ignitor ports).
  - ID liner in pristine condition

Inner & Outer JTAGG I Combustion Liners



ANSIS RESULTS

T=2050F



T=1400F

Post Test Analysis

Outer liner cracked due to stress rupture
- Total Stess = 16.8ksi
- thermal stress = 15.8 ksi
- Pressure stress = 1 ksi

HPT Nozzle/Shroud Program
JTDE (XTE77SE)
General Electric Aircraft Engines

OBJECTIVES

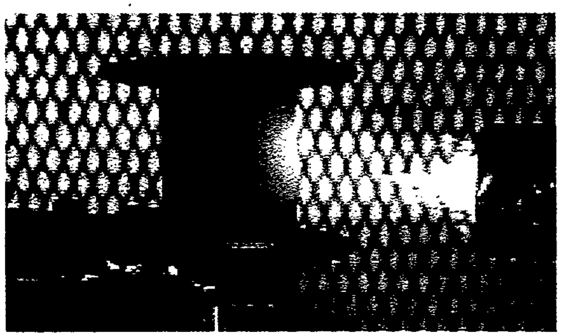
- Design, fabricate, and component test a CMC nozzle
- Transition techology to F414 Upgrade.

TECHNICAL CHALLENGES

- Ability to provide effective cooling to CMC airfoil shapes
- Mechanical design of a CMC vane to survive a high thermal gradient environment
- Ability to provide sufficient structural integrity using CMC material properties
- Attachments to a metallic engine structure in a high thermal differential environment

APPROACH

- Utilize CMC experience gained through other programs
- Examine processing concerns and thermal shock capability using test specimens
- Explore various concepts during the preliminary design phase - integration of airfoils with platform, Trailing Edge, etc.
- Final design, fabricate and rig test most promising design concept



NAVY BAA 6.2 CMC HPT Nozzle
- 3D preform
- Flame testing

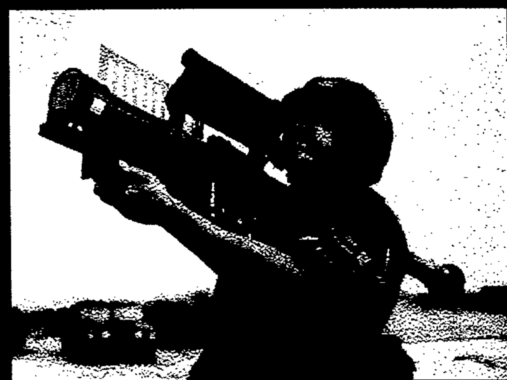
MAJOR MILESTONES

- Coupon thermal and mechanical tests (9/1999)
- Design of nozzle for rig test (6/2000)
- Component rig test, partial engine set (6/2001)

CONTRIBUTION to TECHNICAL EFFORT OBJECTIVE(S)

- Significant increase in T4.1
- Weight reduction (~50%)
- Reduced engine cooling requirements (10% less for nozzle)

Navy IR Survivability Assessment



- Increased Rotary Wing Aircraft Survivability Against Current & Emerging Threat Systems
  - Man portable surface to air heat seeking msls.

- CH-60, SH-60R and AH-1, UH-1

• Phase I - Develop a preliminary design of a CH- 60 / SH- 60R Advanced IR Exhaust Suppressor	March 1998 - February 2000	$650K
• Phase II - Fabricate one flight worthy suppressor unit for ground test demonstration using production materials and processes.	March 1999 - April 2000	$1.15M
Ground Demo with CMC nozzle	<u>Sept. 00</u>	<u>(CMC MANTECH PROGRAM)</u>
• Phase III - Flight Test production suppressor	April 2000 - December 2001	$1.5M

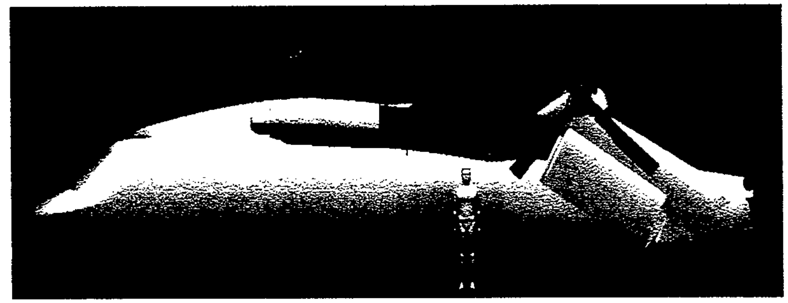
NAVY MANTECH manufacturing technology program

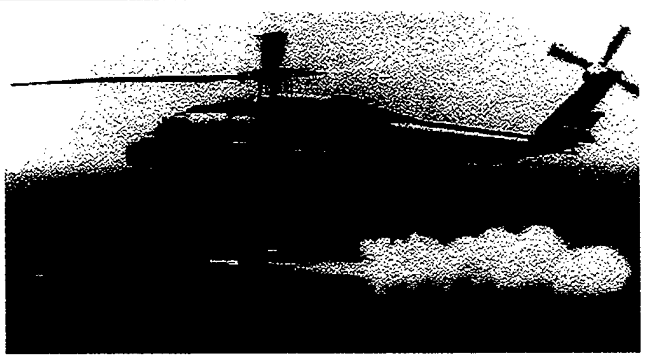
MANTECH: CERAMCO

(Official Kickoff: Jan. 20, 2000)

BACKGROUND

- Develop affordable CMC Manufacturing Techniques for Cost Effective Applications.
  - Aircraft Structures for IR Suppression.
- Program Complements Navy's Advanced IR System Development Program(replace HERRS system) for H-60.
  - Leveraged off Army/Sikorsky CRADA that flight tested an advanced H-60 suppressor system.
  - flight test scheduled for Q2, 2001.





SH60B SEAHAWK

PROGRAM INFORMATION

- **Start/End:** October 1999 - October 2001
- **Sponsor:** H-60, H-1 also UAV & V-22 interests (multiple targeted helicopter platforms).
- **Contractor Teams:**

Team 1: Sikorsky, Composite Optics Ceramics Inc.
Team 2: BellHelicopter Textron Inc., COI

Sikorsky
A United Technologies Company

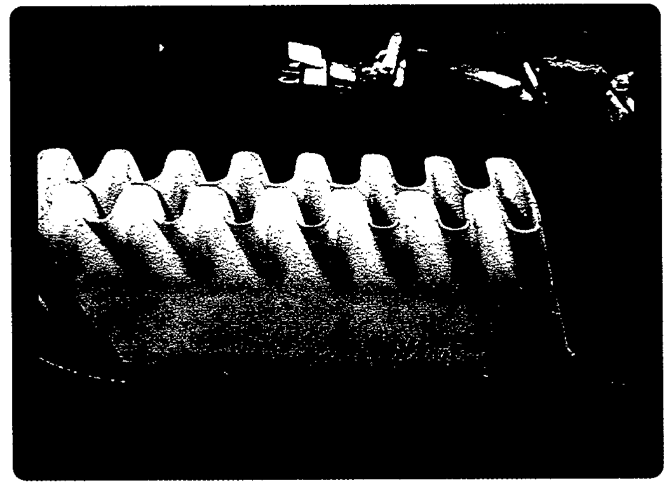
Bell Helicopter TEXTRON

AEROMAT 2000

NAVY MANTECH manufacturing technology program

MANTECH: CERAMCO (TEAM 1)

- **Team 1:** Sikorsky Aircraft, Composite Optics Ceramics, Inc. (COCI)
- **Objective:** Develop affordable and reproducible CMC Processing and Manufacturing for complex shaped exhaust washed Aircraft Structures - CMC nozzles for IR system. H60 Max exhuaust temp = 1200F.
- **Benefit:** Acquisition Cost Avoidance, Weight savings.
- **System Impacted:** H-60 Helicopter Platform, Nozzles for Advanced IR suppressor system.



Ceramic Matrix Composite Nozzle

H-60 Sea Hawk

Program Status

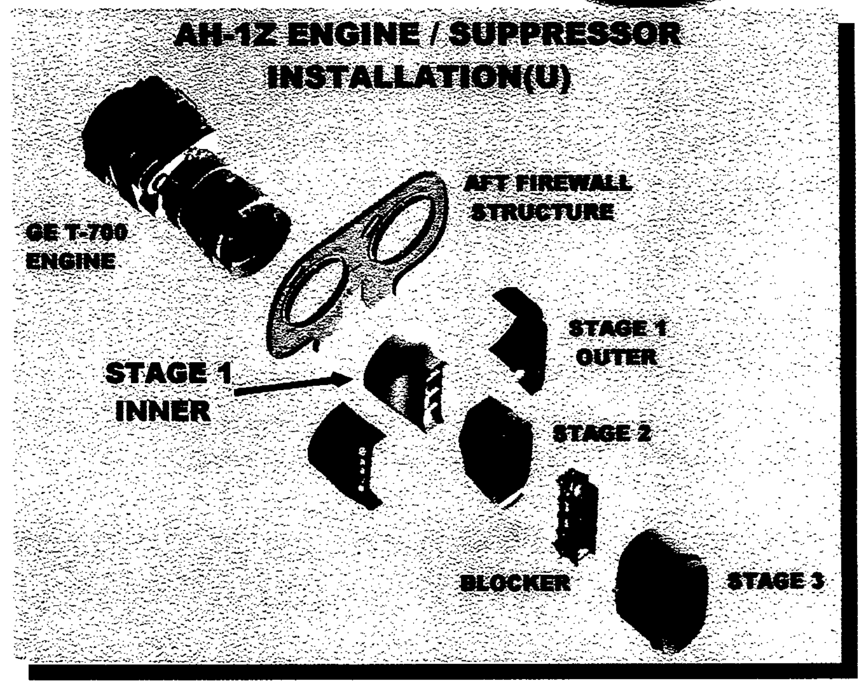
- Material System: Oxide-Oxide (sol gel alumino-silicate), Nextel 610, 8HS. Max operating temp = 1800F.
- Completed Manufacturing/Producibility Assessment of the H-60 Nozzle Geometry. Fabricated Two Full-Scale Proof-of-Concept Articles.
- Completed materials properties (RT, 1200F), Initiated: Effects of Defects, NDI, and Repair Development Tasks.

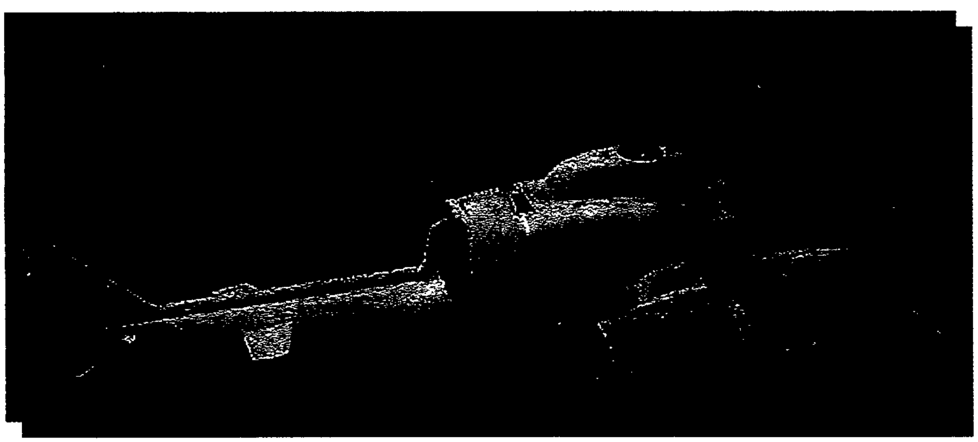
MANTECH: CERAMCO (TEAM 2)

NAVY MANTECH manufacturing technology program

- **Team 2:** Bell Helicopter Textron Inc., System Integrator

  Composite Optics, Material & Component Fabricator
- **Objective/Focus:** Develop and demonstrate affordable & reproducible manufacturing of CMCs for air vehicle applications
- **Benefit:** Acquisition Cost Avoidance- Lower initial cost as compared to existing stainless steel component, weight savings, survivability enhancement
- **System Impacted:** AH-1W, AH-1Z Cobra and UH-1Y Huey Helicopters Stage 1 IR suppressor





AH-1W Super Cobra

Program Status
- Contract work initiated Dec 1999
- Identified AH-1Z / UH-1Y Stage 1 Exhaust Suppressor as candidate component.
- Identified Nextel 610/Alumino Silicate as material system
- AH-1Z / UH-1Y Stage I inner duct non-flightworthy demonstration component being fabricated

Bell Helicopter TEXTRON

NAVY MANTECH
manufacturing technology program

DEMONSTRATION COMPONENT
AH-1Z / UH-1Y SUPPRESSOR STAGE I INNER DUCT

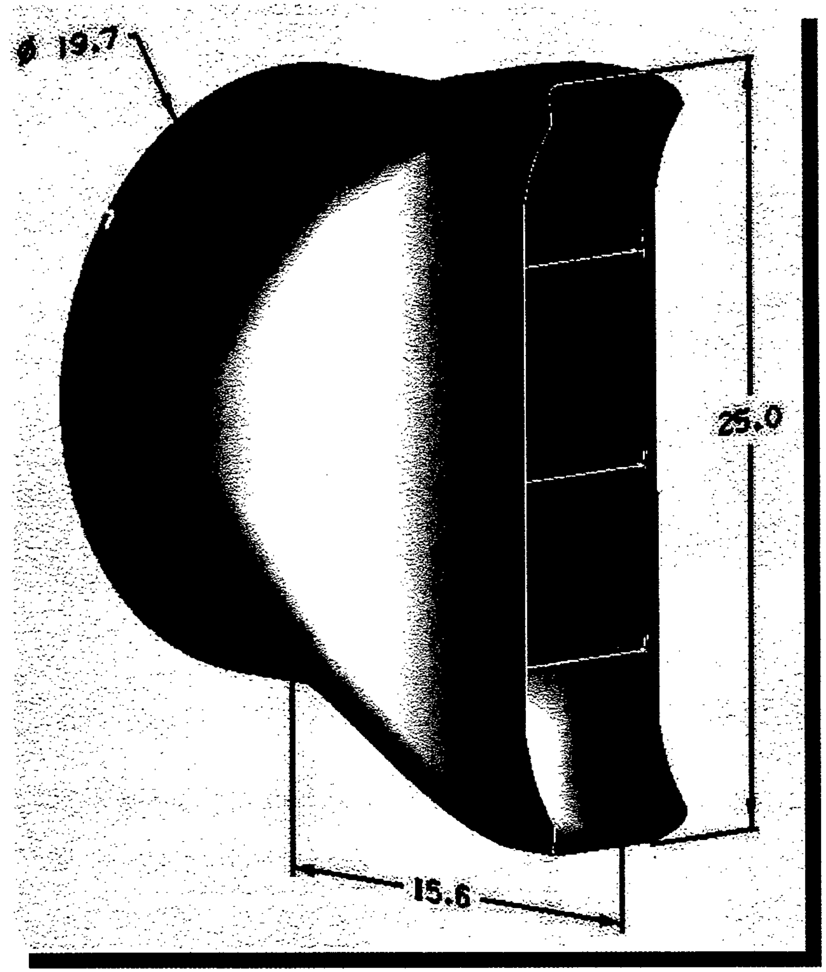
BHTI Part Number: 209-064-218-103

Material: 0.040” stainless steel

Weight: 12.8 lb

Max. Operating Temp: 1220°F

Max. Continuous Power Temp: 1100°F



Bell Helicopter TEXTRON

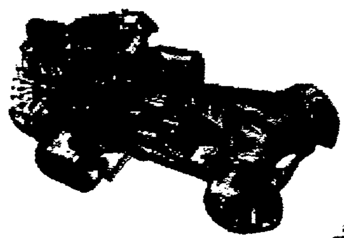
CMC HPT VANE INSERTS

Background: Thermal Fatigue of hpt vane leading edge.
- hot spots up to 2280 F
- thermal gradients > 600F

Loss of aircraft, Sept 1, 1995; double vane burn thru and outer platform release (into gas path).

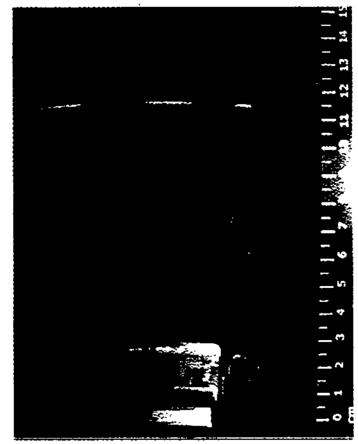
Approach: Insert SiC/SiC CMC shield to reduce the metal vane temperature and thermal gradients at the leading edge.

Benefits: Increase component Life, Increase operating temperatures (408 engine upgrade), Eliminate leading edge cooling holes.

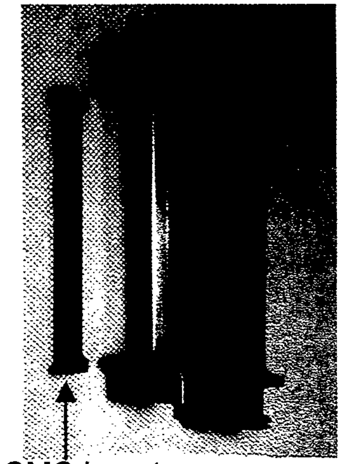


Pegasus F402-RR-406 engine

AV8 Harrier



HPT2 vane doublet removed from service



Status:

- Program is complete, application looking for a home.
- Burner Rig Insert testing results:

- CMC withstood thermal shock, CMC/metal attachment design worked, no sign of thermal fatigue cracks in metal vanes
- Metal leading edge temp reduced (only) 50Fwith insert.
- MI SiC/SiC 2x decrease in surface temp vrs. CVI SiC/SiC.
- Rig testing continuing at NASA to test possibility of ellim-nating the cooling hole requirement.

- 406 engine is being phased out in 2 years, engine life has been reduced from 1000 to 500 hrs.
- 408 engine upgrade is going with a redesigned vane -sand tolerant design, revised inner cooling scheme.

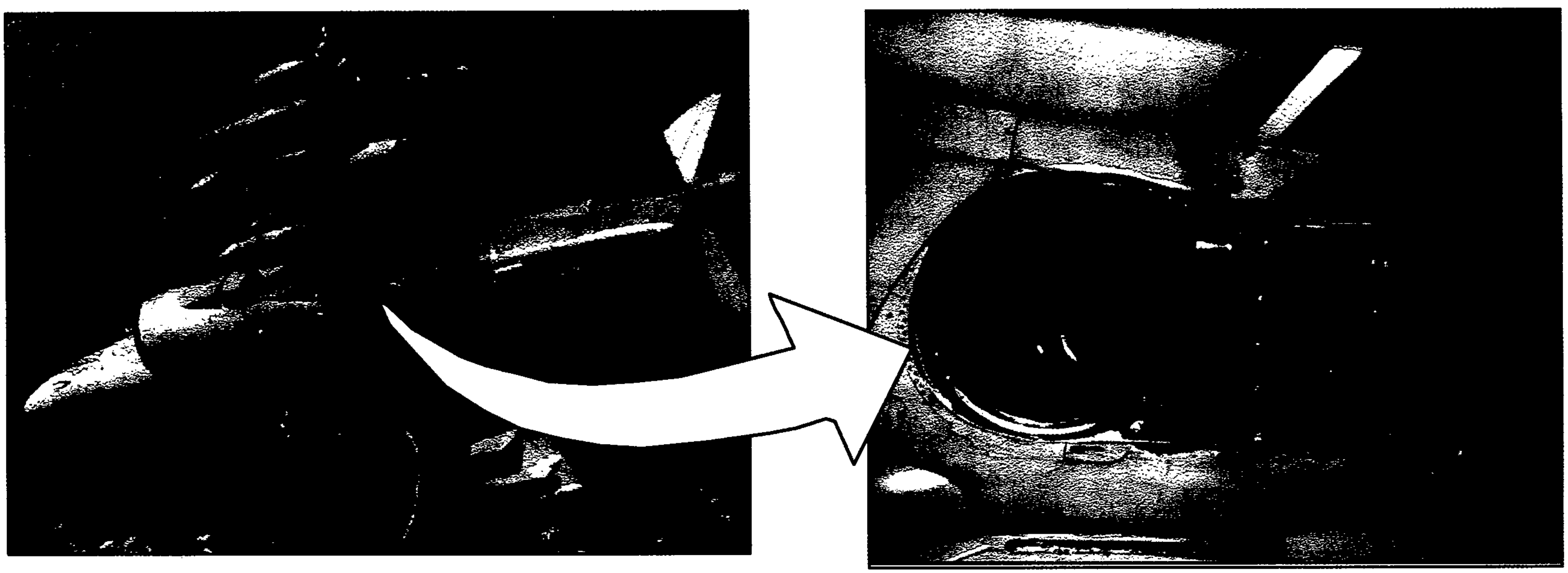
FLIGHT TEST OF CMC BLASTSHIELD

AV-8B Harrier heatshield (a stainless steel exhaust blastshield) is subjected to an extreme thermal and acoustic environment which leads to short service life.

- Component begins to crack after few flight hours requiring frequent stop-drilling repairs.
- Northrop Grumman identified this component as ideal for demonstrating the company CMC experience.
- A cooperative IR&D programwith NG and MDC (now Boeing) designed and fabricated 2 heatshields.

\- Nextel/Blackglass (Silicon-Oxy-Carbide via polymer pyrolisis), cmc system capability 1500F, component sees 900F.

- Ground engine and flight testing successfully completed in 1997.



- Non-destructive inspection following flight showed no deterioration of the component.
- Second blast shield remains available for future flight and endurance testing.

SBIR

REPAIR OF CMC's FOR EXHAUST WASHED STRUCTURES

BACKGROUND

- Existing AV-8B Metallic Blastshield Degrades Under Extreme Thermo-Acoustic Environment Creating Significant Maintenance Burden
- NGC Has Demonstrated Prototype Nicalon/Blackglas Blastshields
- **Prior To Fleet Introduction, Repair Approaches Are Required To Be Developed**

APPROACH

- Issue Phase I SBIR For The Development of Repair Procedures
- Phase II SBIR Will Demonstrate Repair Approach By Testing a Repaired Blastshield Under Thermo-Acoustic Conditions
- Team With AFRL For Acoustic Testing

STATUS

- Preliminary Repair Designs Have Been Developed
- Phase I Option Currently Evaluating Matrix Re-Impregnation Approach
- Phase II Program Expected To Start May 2000

PROGRAM INFORMATION

- Sponsor: AV-8B Program Office
- Contractor: Materials Research & Design
Kent Buesking (610) 526-9540
- NAVAIR TPOC: Jerry Rubinsky - NAVAIR Structures
(301)-342-9355

NORTHROP GRUMMAN

SOUTHERN RESEARCH INSTITUTE

AEROMAT 2000

F110-GE-400 Flameholder Ceramic Insertion

NAVAIR Component Improvement Program/ARPA Ceramic Insertion Program

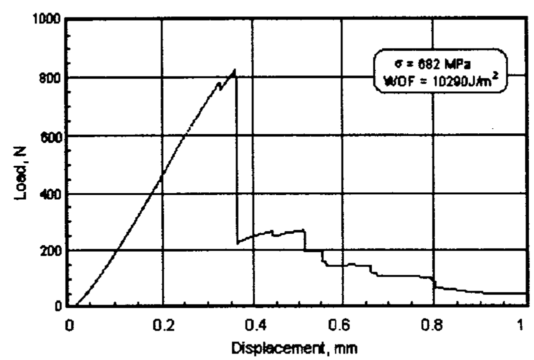
Design and Develop a ceramic flameholder more durable than current HS188 (Ni-Co superalloy)
- thermal cycling stress → cracking, creep, erosion

Navy Benefits

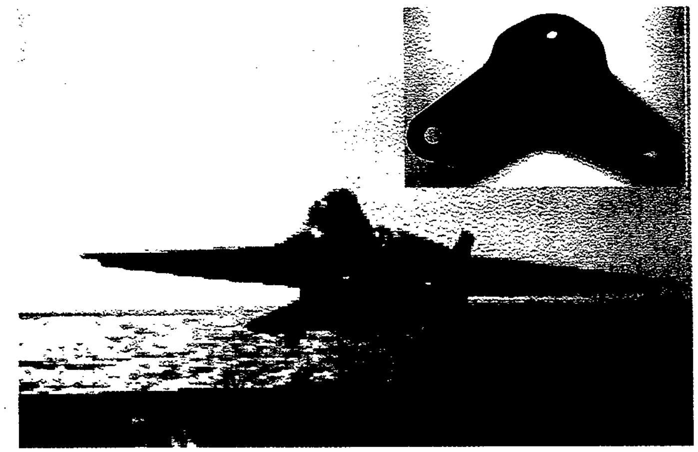
- Reduced support costs - fewer replacements, mtbf = 1000EFH
- Improved mission readiness
- Safety - reduce potential for direct flame impingement on A/B liner

Approach

Attach (24) ceramic inserts to highly stressed "hot" spots on the flameholder assembly. ACR silicon nitride FM chosen based on cost and graceful failure mode.



advanced ceramics research



GEAE F110 platform for F-14, F-15 and F-16 aircraft platforms.

Status

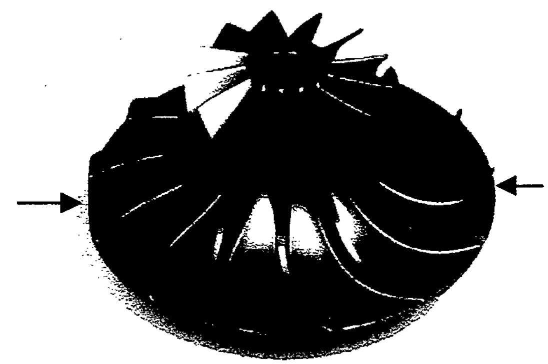
- Initial engine tests with BFG SiC/C CMC
  - demonstrated need for redesign of attachment.
- CMC elliminated from consideration due to cost
- Silicon Nitride Fibrous Monolith was engine tested
-HS188 metal attachment failed (thermal stress).

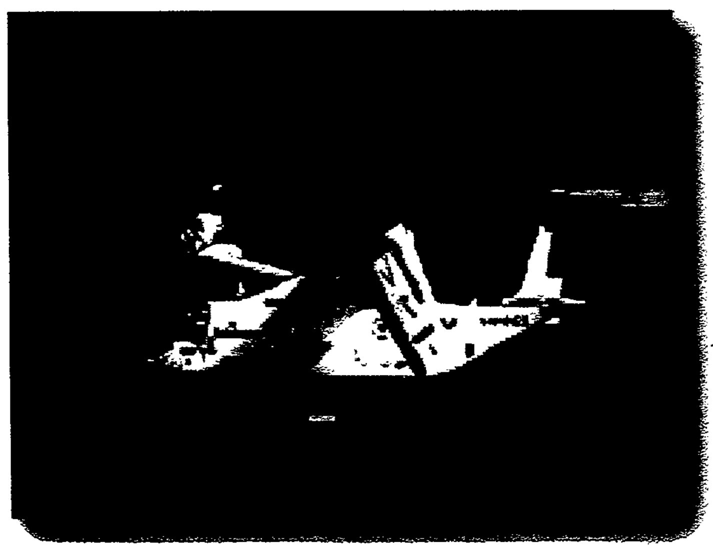
CERAMIC IMPELLER for V-22 SHAFT DRIVEN COMPRESSOR

Problem:
Honeywell manufactured Shaft-Driven-Compressor Impeller (100k rpm) is experiencing short (200-300 hr) life due to sand erosion.

Approach:
Replace existing Ti-6Al-4V impeller with Honeywell's GS-44 in-situ reinforced silicon nitride.

Developmental Program:
ONR TOC Initiative, Start FY02





V22

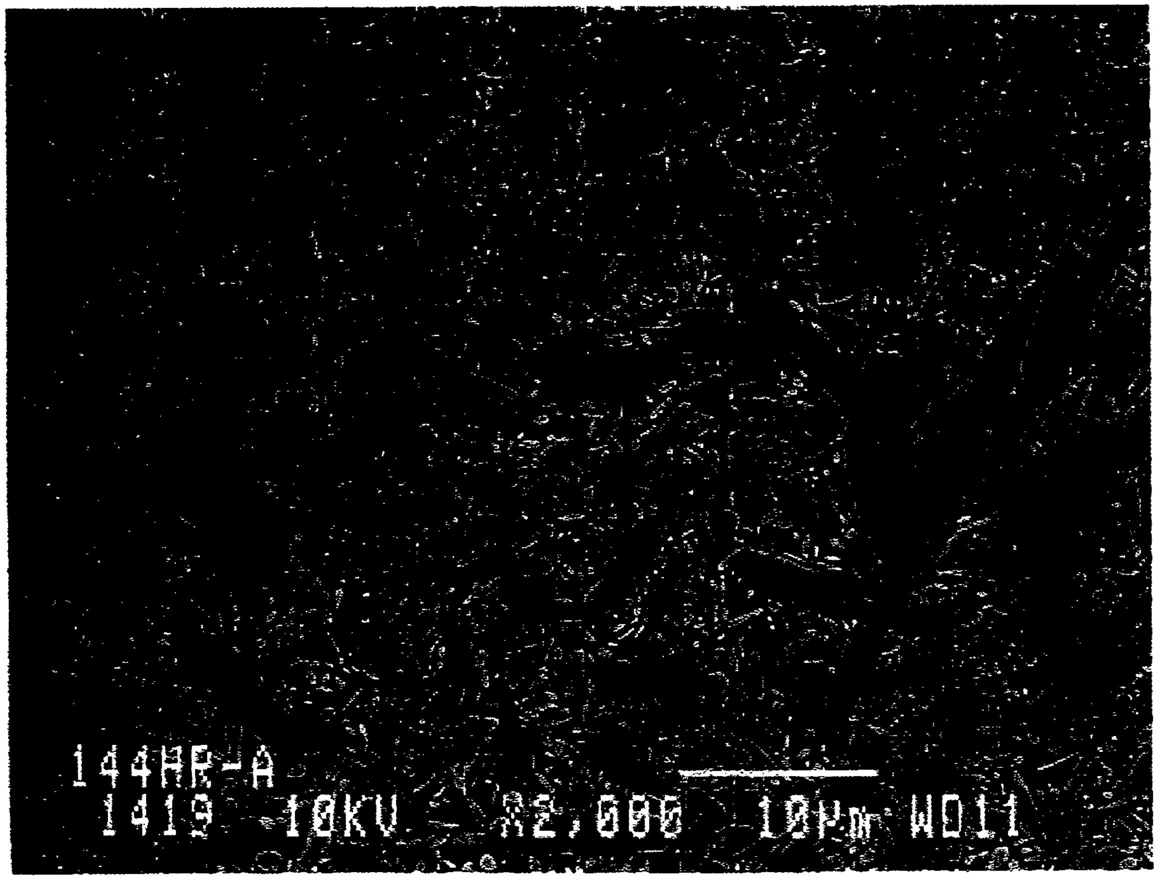
Benefits:
- Extended component life from (10x) improved erosion resistance.
- Reduced component and containment weight.
- Total Ownership Cost (TOC) reduction = $ 121M
  - includes O level and D level replacement costs
  - significant reduction in spares requirement over existing Ti component.

Implementation Program (FY03 Start)
- Tasks approved, V22 program funds set aside contingent on successful developmental program.

Honeywell

AEROMAT 2000

[redacted]



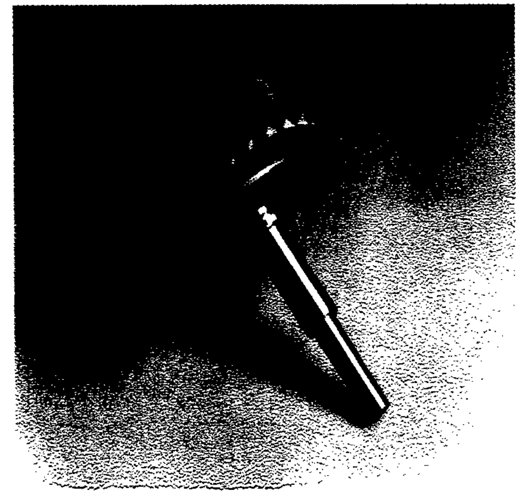
RT Flex Strength = 1051MPa
Weibull Modulus = 20-30
Fracture Tough. = 8.25 Mpa * m1/2

Density = 3.2 g/cc
Elastic Modulus = 300 GPa
Hardness = 1460 GPa

Relevant Experience

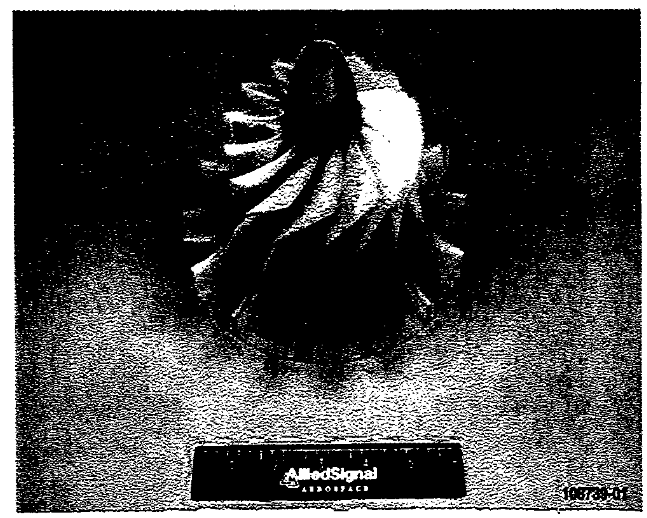
B52 - Air Starter Wheel (Gelcast)

- 5.0" Diameter (tip speed 2182 ft/sec)
- 100K RPM Operational (125K RPM Proof)
- Metal Shaft Attachment
  - 0.8 inch diameter
  - 160 ft-lb Static Torque at 400 degrees F
  - > 250 ft-lb Static Torque at 70 degrees F



Power Turbine Rotor (Gelcast)

- 7.0" Diameter (tip speed 1985 ft/sec)
- 65K RPM Operational (88K RPM Proof)



Status

- Design modifications to gel-cast mold to eliminate air pockets/bubbles.
- Engine Rig Test.

BURST TEST AND CONTAINMENT
Starter Wheel

55% weight savings in the containment ring
when a silicon nitride ceramic turbine wheel
replaces a metal wheel